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MANNED UNDERSEA STRUCTURES - THE ROCK-SITE CONCEPT

by

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Research Department

ABSTRACT. Large undersea installations with a shirt-sleeve environment have existed under the continental shelves for many decades. The technology now exists, using off-the-shelf petroleum, mining, submarine, and nuclear equipment, to establish permanent manned installations within the sea floor that do not have any air umbilical or other connection with the land or water surface, yet maintain a normal one-atmosphere environment within. This presentation briefly reviews the past and present in-the-sea-floor mineral industry. The methods presently practical for direct access to and from permanent in-the-sea-floor installations are outlined, and the specific operations and types of tools indicated. Initial power requirements and cost estimates are included.

U.S. NAVAL ORDNANCE TEST STATION
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FOREWORD

This report summarizes concepts developed through extensive literature and field studies as a part of the continuing investigation of the undersea environment and its utilization.

The work was performed during Fiscal Year 1966. Both the studies and preparation of this report were supported by Independent Exploratory Development, Bureau of Naval Weapons Task Assignment R361-00 000/216-1/F008-98-16.

This report has been reviewed for technical accuracy by Donald K. Moore, David W. Scholl, and George A. Wilkins.

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INTRODUCTION

Permanent manned installations at the bottom of the sea is a goal that is being actively pursued by many nations, by many governmental agencies within our own nation, and by various industrial concerns. The recent report by the Panel of Oceanography of the President"s Science Advisory Committee has emphasized this nation's interest in the sea and has listed a series of priorities for efforts in oceanography that deal with national security (Ref. 1). Among the requirements for achieving the needed deep-ocean capability is the ability to establish large working spaces with a one-atmosphere environment beneath the ocean surface.

Two concepts for achieving manned undersea installations have received considerable public notice in recent months. One of these is the saturation diving technique, which is being pursued in the Sea Lab studies. The second, a method of achieving a one-atmosphere working space in the deep sea, is to construct and use bottom-sitting structures, either fully prefabricated or assembled on the bottom. One of the more complex of the latter is the "bottom-fix" proposal for the mid-Atlantic ridge by General Electric (Ref. 2).

These two methods of achieving manned undersea installations are certainly practical for some uses, and at least for small installations are definitely feasible with today's technology, although only Sea Lab has been well-demonstrated to date. There is, however, a third concept for manned undersea installations, and furthermore, installations that are feasible with today's tools and technology. This concept, being pursued at the U. S. Naval Ordnance Test Station, is called "Rock Site." In brief, a Rock-Site installation consists of a room or series of rooms, excavated within the bedrock beneath the sea floor, using the in situ bedrock as the construction material. These installations exist today, established by industry, and they have existed for decades. As an immediate illustration of the practicality of this approach, consider Fig. 1. The room shown in this photograph is a machine shop excavated in bedrock beneath the sea floor and is located off the eastern coast of Canada. This particular installation has 7½ square miles of permanent floor space beneath the sea floor, an area that would be difficult to duplicate using prefabricated structures. The depth of water above the shop area is 100 feet, and in winter this water is capped by several feet of drift ice. The distance offshore is 2½ miles.

A series of openings, such as the one in Fig. 1, could obviously contain an extensive repair and supply capability for the support of undersea operations. An installation with several square miles of useful floor beneath 1,100 feet of rock, as in the case of Fig. 1, could be a major community with full family and recreational living facilities as comfortable as those in any city building. Located along the mid-Atlantic ridge or on selected seamounts, the potential for research from this type of site becomes large, since the site, though immobile, is also unsinkable.

FIG. 1. Undersea Machine Shop off the Coast of Newfoundland. Located 1,500 feet below sea level, beneath 400 feet of water (Wabana).

This report will discuss the findings to date of a study program regarding the Rock-Site concept per se and will review the problems and needs pertinent to establishing Rock-Site-type installations within the bedrock beneath the sea floor today, using only today's tooling and technology.

HISTORICAL REVIEW

Industrially established working sites with a one-atmosphere environment have existed beneath the sea floor for many years. The first such installation under the continental shelves of North America was begun in 1867 off the coast of Cape Breton, Nova Scotia, and was dug using hand labor. Surely modern mechanized mining methods can do as well today.

On a world-wide basis, a study of the literature of undersea mining shows that manned installations within the sea floor have been carried out with varying degrees of success in Australia, Canada, Chile, England, Finland, France, Greece, Ireland, Japan, Poland, Spain, Taiwan, Turkey, and the United States. At least 75 companies or mining installations have been involved in these undersea activities. Commodities mined beneath the sea floor by means of manned undersea installations include coal, iron ore, nickel-copper ores, tin, gold, and limestone. Some of these undersea mining complexes, in existence today, spread across many tens of square miles of continental shelf and measure their workings in terms of thousands of miles of linear openings. Most of the present-day undersea mining installations that are beneath the sea floor are little known outside of the mining fraternity, and are not too well known even there. Inquiries to mining associations and to governmental agencies in countries with known undersea operations bring conflicting reports and even statements indicating a complete lack of knowledge of the existence of such operations.

As an operating example of an undersea installation off the coast of North America, the Dominion Coal operations adjacent to Cape Breton have an enviable record of safe and successful undersea coal mining. The Dominion Coal operations are a complex of many consolidated undersea mines ranging in depth from 200 to 2,700 feet below the sea floor, with a water cover of 60 to 100 feet. These mines span an area of approximately 75 square miles and presently employ some 4,100 men in the undersea workings.

The available literature on mining operations conducted beneath the sea floor is extensive, but articles dealing specifically with the problems and hazards resulting from the hydrostatic load above are few, and the literature describing mine floodings and disasters due to water inflows and other possible problems is quite scanty. A review of the literature on underwater mines is presented as a part of the reference section. References to mines situated beneath large lakes and rivers have been omitted, though many such mines exist. Furthermore, the reference section excludes the literature of "sandhog" or other pressurized, shallow operations, and has completely omitted the vast and voluminous literature on the English Channel crossing, most of which consists of outdated speculations and politically based arguments. The reference list on undersea mines includes only deep and extensive undersea activities. Broad descriptive articles on undersea operations comprise Ref. 3-60, with the paper by Gray (Ref. 28) especially well done. Articles with descriptions of undersea accidents due to unexpected breakthroughs into the sea floor or to other problems pertinent to the undersea environment comprise Ref. 61-70. Historically, undersea mining has been no more troublesome than the same type of operations carried out beneath an ordinary land surface. Indeed, at the present time, the best examples of mine floodings and, in particular, of mine operations within zones of high water pressures are to be found on land (Ref. 71 and 72). Catastrophic water inflows in undersea mines, discounting seepages and flows that originate on adjacent land and migrate down the bedding to beneath the sea, have generally been the result of mining too close to the sea floor; the result of over-extractions followed by widespread collapse in attempts to prolong the life of a mine, or the result of a failure to keep pilot holes ahead in areas of questionable water flow potential or uncertain bedrock topography.

Figure 1 shows the size of a single room that one operating company has been able to safely achieve under the sea floor in a strong sediment, in this instance an iron ore (hematite) overlain by two thin conglomerate beds and an extensive section of shale. Figures 2-6, all taken underneath the sea floor off the coast of Cape Breton, show a series of machinery installations illustrating the continued and routine operation by industry of large complex hydraulic mechanical and electrical equipment at various depths beneath the sea floor while Fig. 7-9 illustrate underground warehousing and rail transport in the Wabana operations which are 1,500 feet below sea level off the coast of Newfoundland.

Many persons associate mining installations with poor conditions. In large part this stems from the temporary nature of most mine excavations which are intended for only a few weeks or months of use at best. People tend to overlook that the permanent mine installations in an underground operations are generally clean, comfortable, and as well as or better air conditioned than many surface-type industrial plants. Figure 10 shows a typical temporary mining opening 200 feet beneath the sea floor while Fig. 11 shows how a comparable mine opening in the same area has been cleaned up and established as a permanent installation. The distance offshore at which these pictures were taken varies from the coastline to only about 2½ miles, but the pictures serve to illustrate conditions within typical present-day operations beneath the sea floor. The present-day mining industry has for many decades conclusively demonstrated the economic practicality of establishing large manned working spaces with a one-atmosphere environment beneath the ocean floor for the extraction of raw materials.

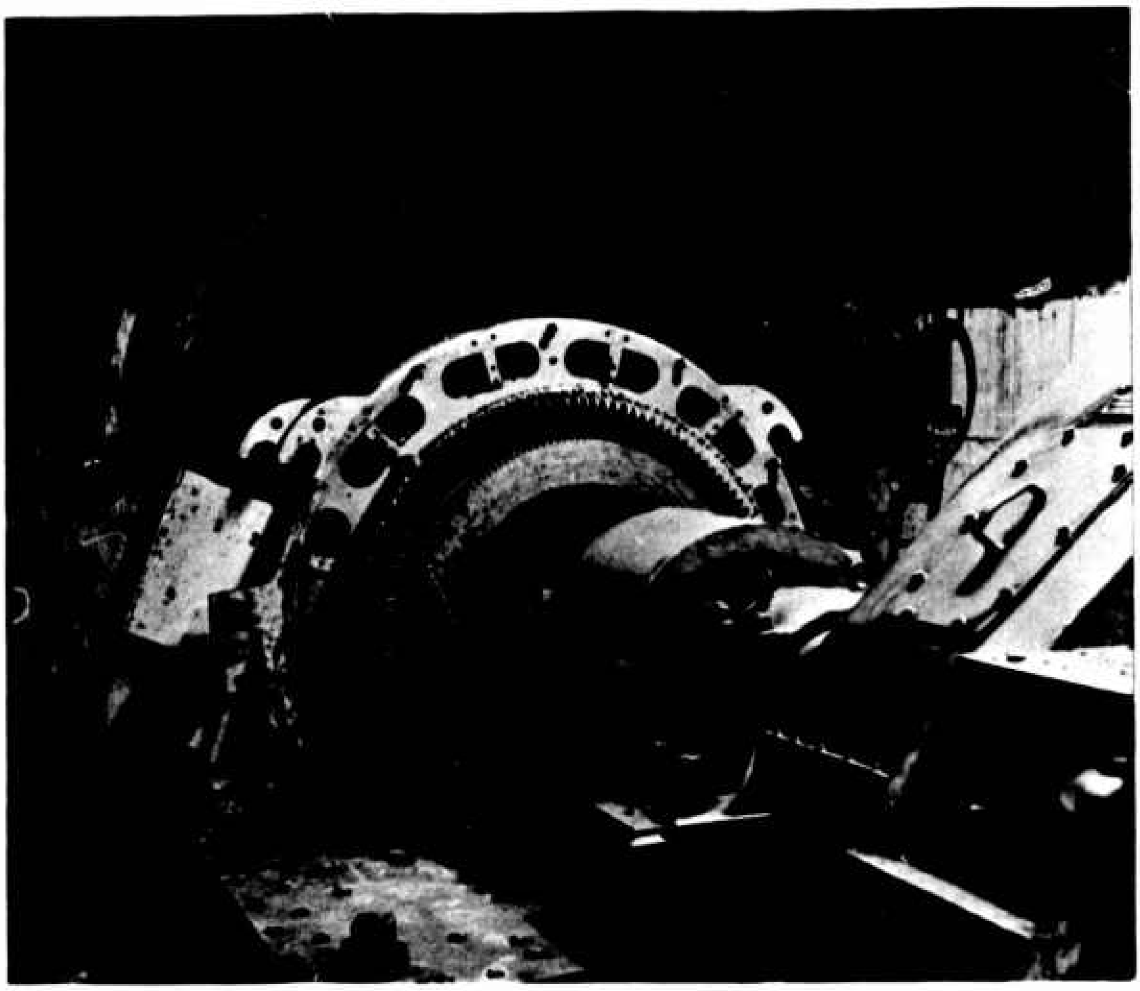

FIG. 2. 1,800-hp Electric Motor Installation. It is 470 feet below sea level and approximately 400 feet below the sea floor (Dominion Coal).

FIG. 3. Hoisting Equipment With Hydraulic and Electro-mechanical Controls. Located 470 feet below the sea level and approximately 400 feet below the sea floor (Dominion Coal).

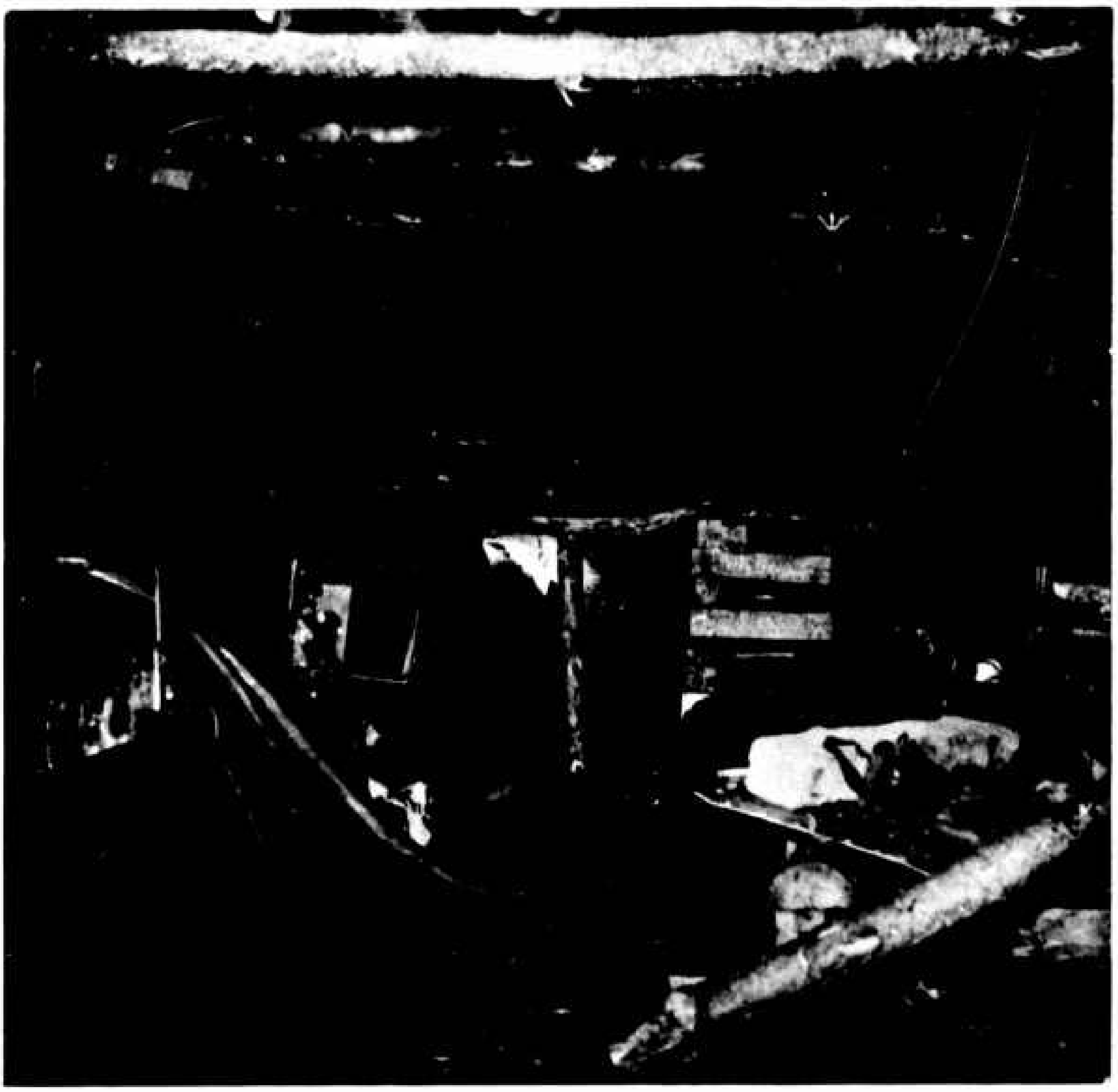

FIG. 4. Conveyor Belt Transfer Point and Loading Facilities. Approximately 3 miles offshore and beneath the continental shelf (Dominion Coal).

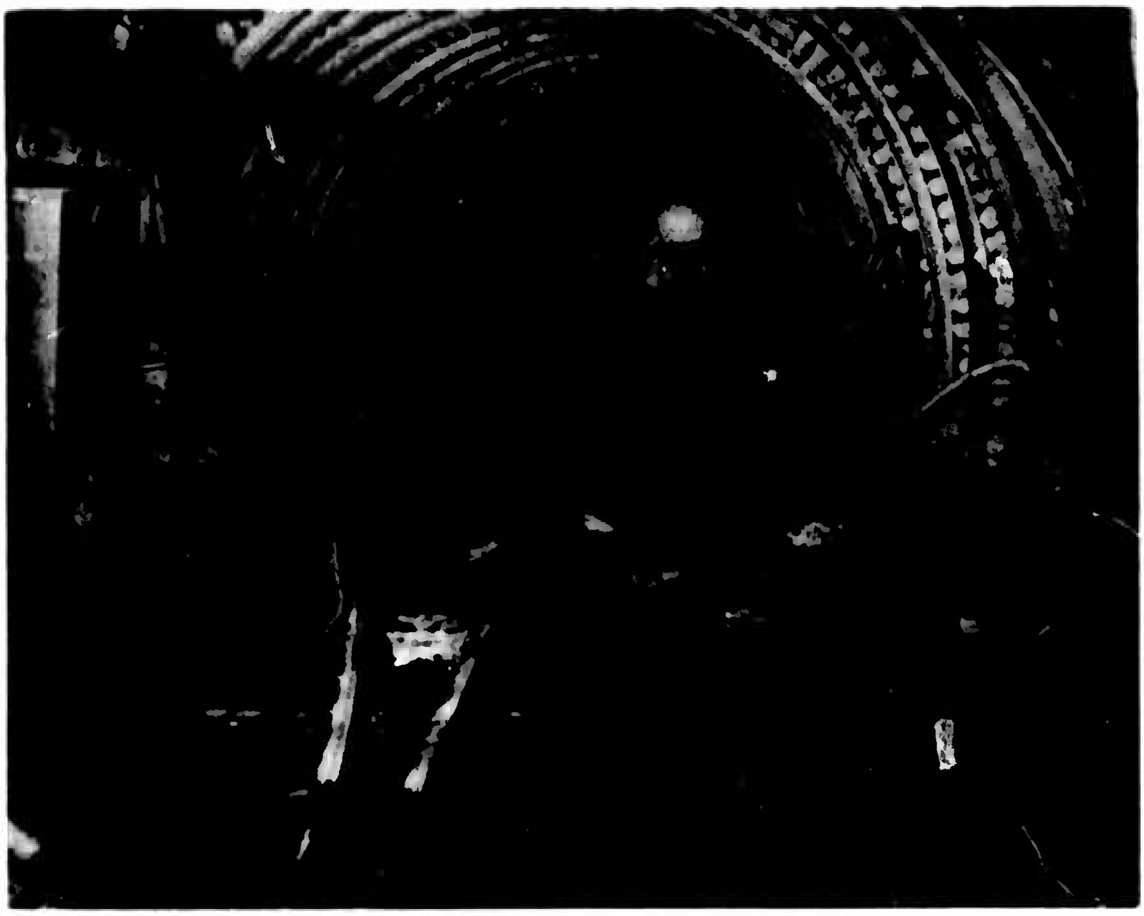

FIG. 5. Rail Haulage. Approximately 3 miles offshore and beneath the continental shelf (Dominion Coal).

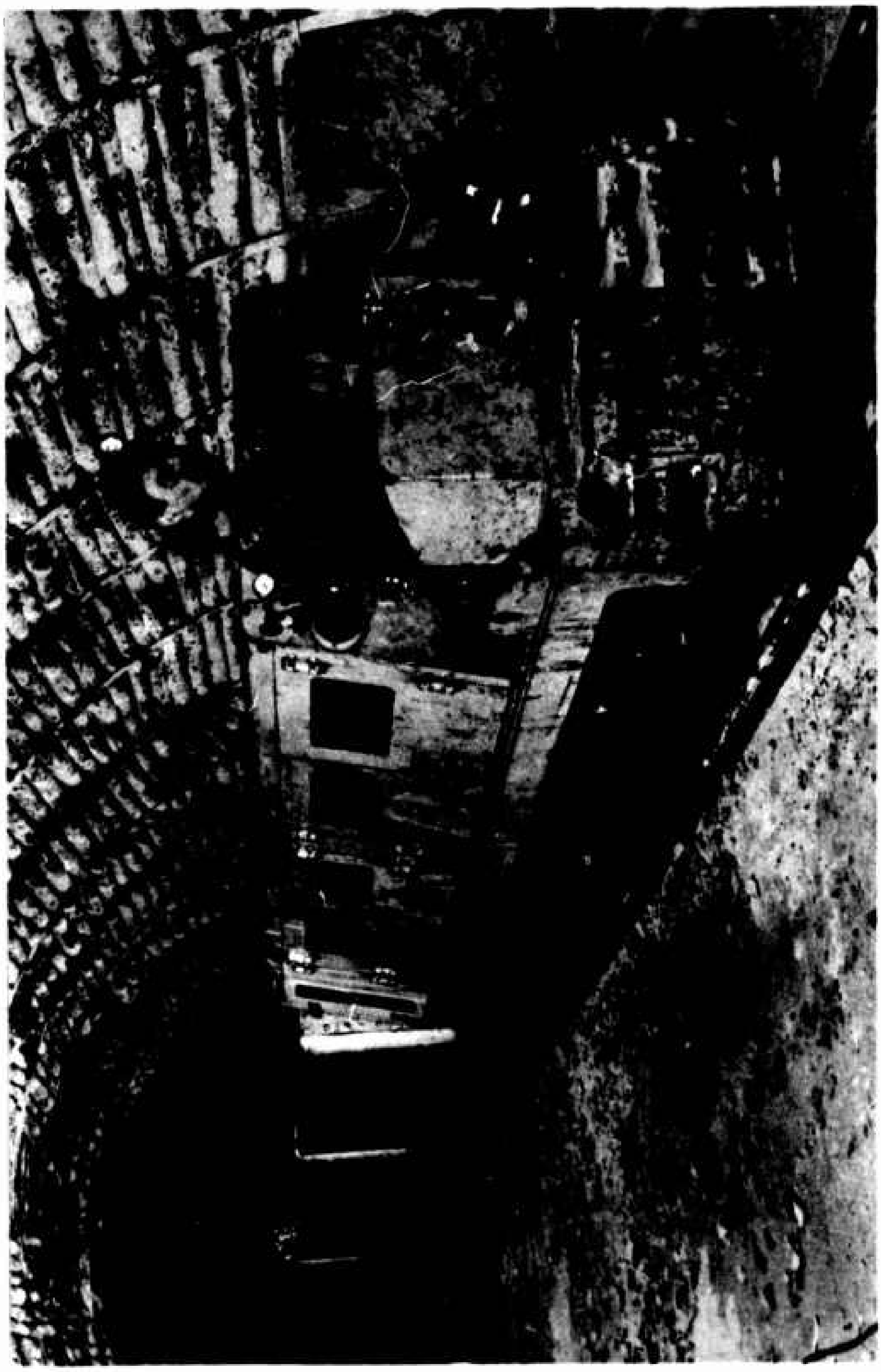

FIG. 6. Diesel Locomotive Operating Beneath the Sea Floor (Dominion Coal).

FIG. 7. Shuttle Car Operations Beneath the Continental Shelf off the Coast of Newfoundland (Wabana).

FIG. 8. Warehouse Installation. It is 2½ miles offshore and 1,500 feet below sea level with a 400-foot water cover (Wabana).

FIG. 9. Rail Transport Facilities. Located 1,500 feet below sea level with a 400-foot water cover (Wabana).

ENTRY INTO THE SEA FLOOR

FROM THE LAND

Industrially established working sites or mines within the sea floor all obtain access to the bedrock beneath the sea floor by means of shafts and tunnels to an adjacent land surface. This land surface can be the mainland as with the John Darling Colliery in Australia, from a natural island, as with the Wabana Mine at Bell Island off the coast of Newfoundland, or from an artificial island as at the Miike Colliery in Japan. Figure 12 shows a vertical shaft which is used in conjunction with a tunnel and slope system to reach coal located under the sea adjacent to Cape Breton, Nova Scotia. Figure 13 shows an inclined shaft used to reach undersea iron ore off the coast of Bell Island, Newfoundland, while Fig. 14 shows an artificial island in use off the coast of Japan for sea-floor access. At these, as with all present-day manned undersea mining installations, a vertical or inclined shaft and tunnel system serves as an air umbilical between the mining operations and the adjacent land surface.

FIG. 10. Typical Temporary Coal Mine Opening After 10 Years of Disuse. In this instance it is located 240 feet beneath the sea floor, with a water cover of 60 feet (Dominion Coal).

FIG. 11. Pump Room. Illustrating how a mine opening can be cleaned up to provide a pleasant working space, in this instance 700 feet below sea level and at the shore line (Dominion Coal).

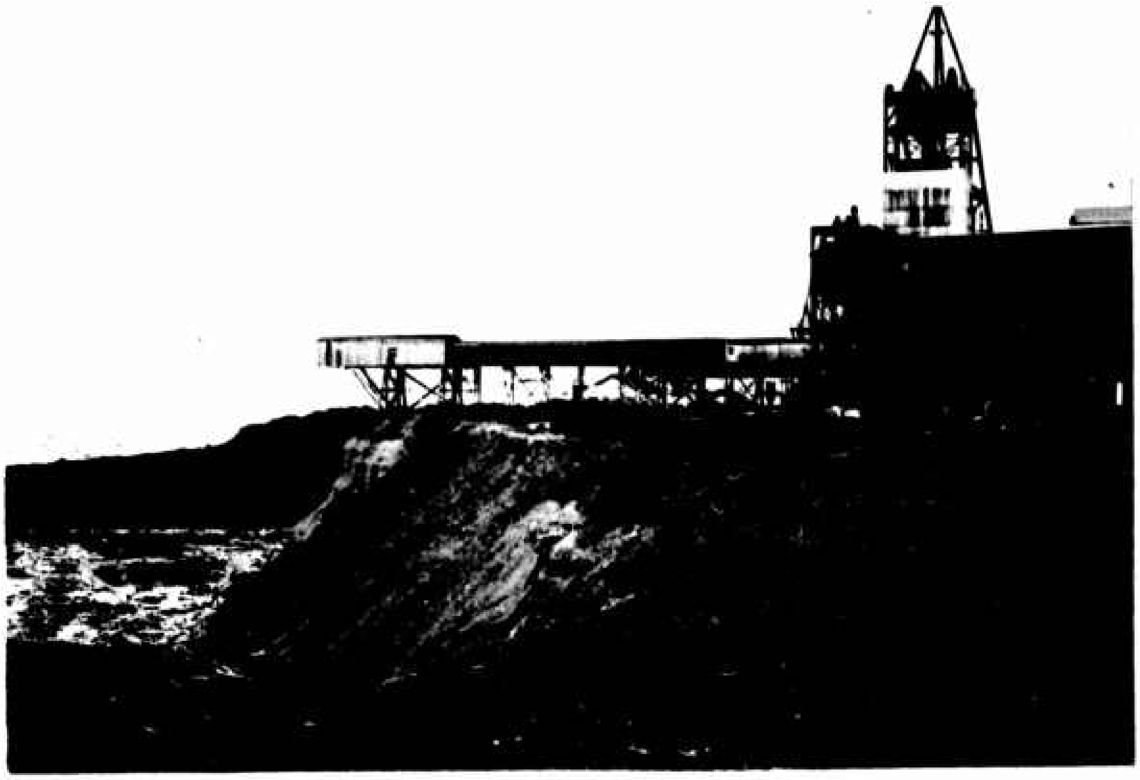

FIG. 12. Vertical Shaft at the Shore Line for Entry into Submarine Coal Mine Workings at Cape Breton.

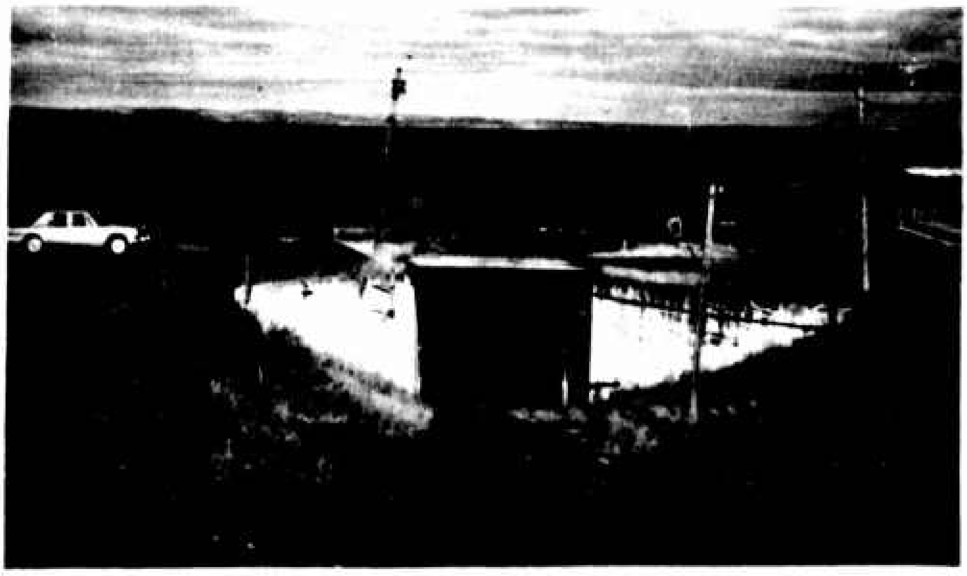

FIG. 13. Inclined Shaft at Bell Island, Newfoundland for Access to a Submarine Iron Mine (Wabana).

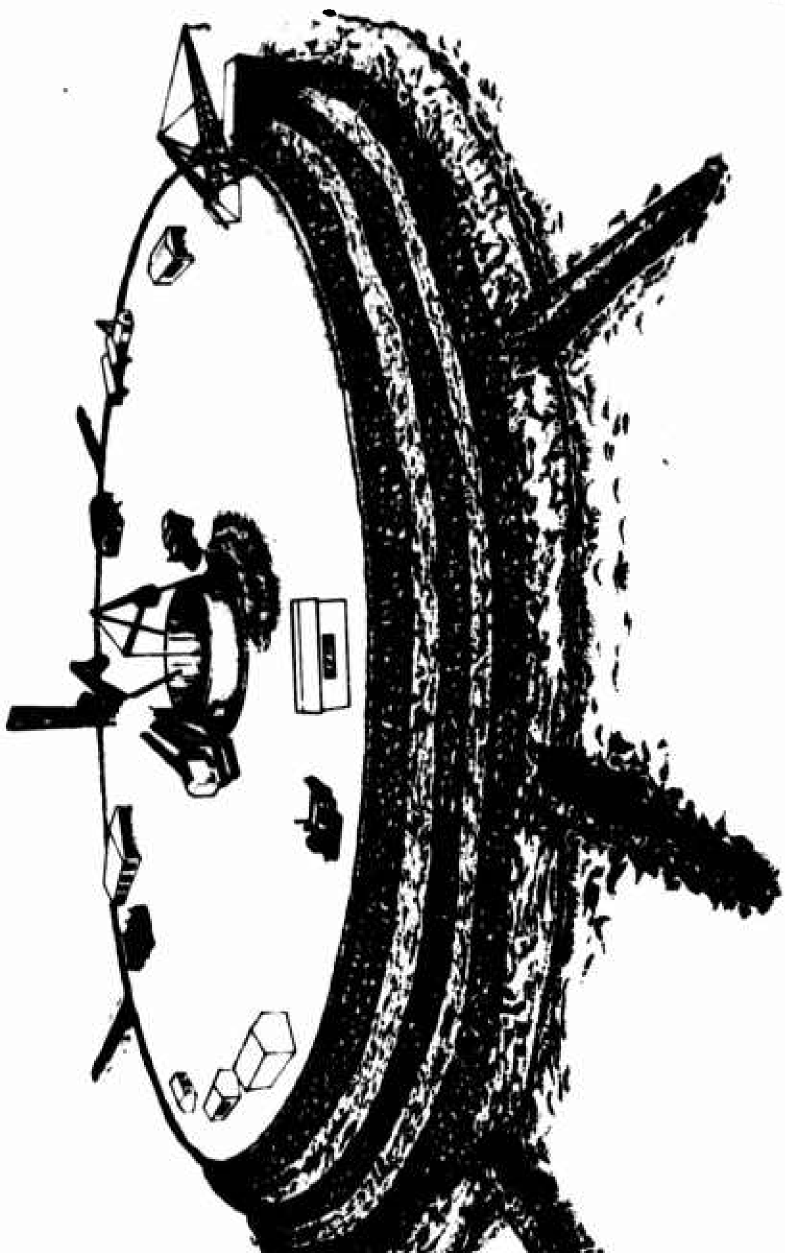

FIG. 14. Artificial Island Located off the Coast of Japan for Access to a Submarine Coal Mine (Miike).

This use of an air umbilical enables present-day undersea installations to obtain all needed power and life support from the surface in the form of compressed air, fan-driven ventilation systems, electricity, and in some instances diesel oil for underground use. The distances offshore to which existing mines can operate is sharply limited by several considerations. As mines move offshore, many also go down dip, that is, follow the coal or ore beds deeper beneath the sea floor. With increasing rock loads, mining becomes more and more expensive and ultimately uneconomical, especially for low value products that must be produced in great volumes. As mines extend further offshore, the transportation of both crews and commercial products becomes more difficult, especially in those mines with fluctuating dips in the rock strata being mined. With increased distance offshore, the provision of sufficient ventilating air becomes a problem. Ventilation is especially a problem with coal mines where large air volumes are needed to dilute the methane released from the coal measures to concentrations well below the explosive limits for air and methane. Present-day mine planners in the coal industry talk of distances of 12 to 15 miles offshore as a possible economic limit for many existing mining operations, though these numbers will unquestionably prove to be conservative.

Installations with an air umbilical back to shore are certainly feasible with today's technology. Figure 15 shows a sketch of such an installation. In this figure, access is by means of a vertical shaft. From this shaft a horizontal opening extends in two directions. One opening leads to a reactor chamber housing, according to present plans, a 5-megawatt-electrical (Mwe) reactor cooled either by convectively circulating sea water or by leakage water derived from the main sump. The second opening leads first to a laboratory and office complex, and then to an experimental access system. Here there are vehicle locks for bringing submersible vehicles into the one-atmosphere environment of the installation and lock tubes, bored both inward and outward for access by means of the Undersea Research Vehicle (URV) and similar types of submersibles. These lock tubes could be for practice in getting into and out of the sea floor without the air umbilical from land, and will also be of great value in testing hatch and access systems.

Land-based undersea installations are not only practical today but are not overly expensive. The depth of shaft needed for a land-based installation will depend on the depth needed to reach either a competent rock horizon beneath the sea floor or else a desired depth from a construction point of view. Assume an installation depth of 1,000 feet below the surface is desired. A probable depth of shaft is then 1,200 feet. Shafts can be excavated by drilling and blasting, but a more usable shaft with far less maintenance and damage to the rock around the shaft will result from boring, a technique just now coming into general industrial use (Ref. 73 and 74). With a bored shaft in the range of 5 to 8 feet in diameter, the cost will be roughly 4 million dollars completed, including the life support and service systems although some industrial firms will now estimate a cost of about 2 million dollars for this size of installation. Large diameter shaft drilling has been well discussed in the literature and extensive charts and graphs for detailed cost estimating are available (Ref. 75).

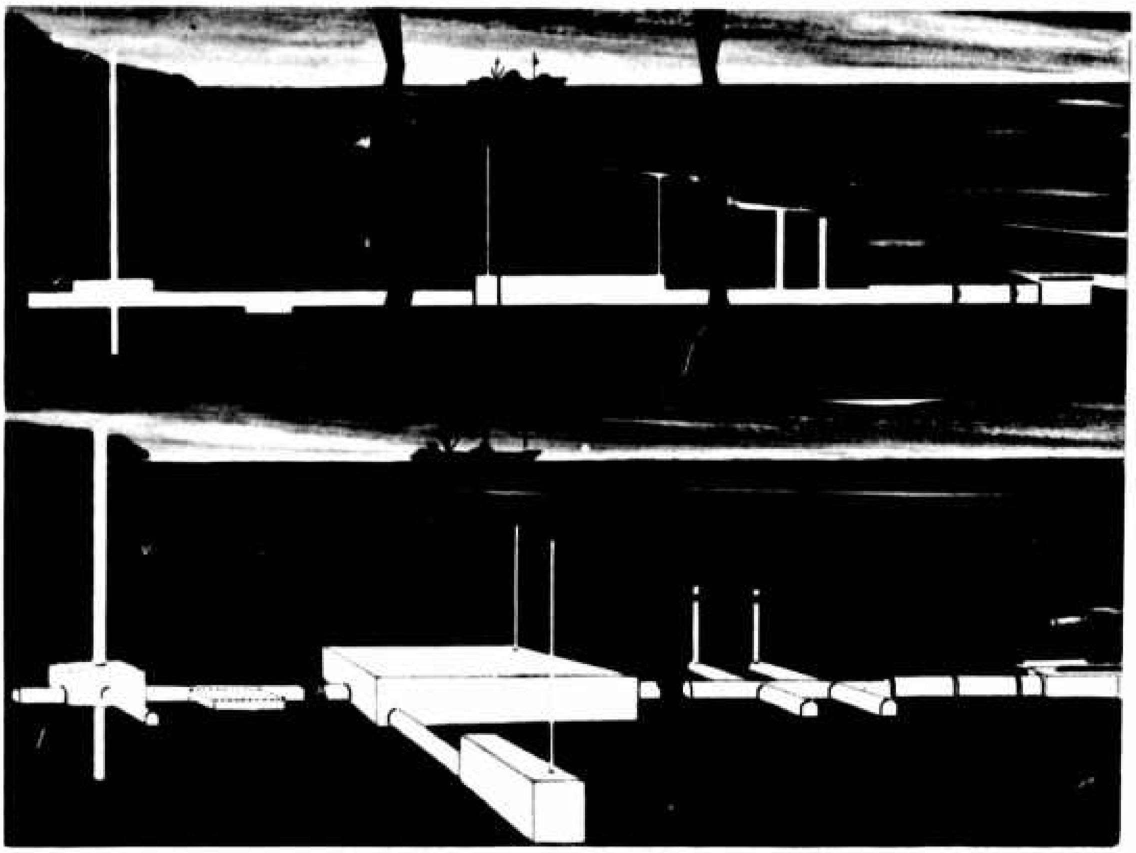

FIG. 15. Undersea Rock-Site Type of Installation Feasible With Today's Technology. Includes a vertical access shaft or "air umbilical," a reactor chamber, drill holes to the sea floor for reactor coolant circulation, a working or laboratory space, two lock tubes to the sea floor, and a vehicle lock.

For long distance undersea tunnelling, boring is especially attractive (Ref. 76–78). Boring methods require only electric power, and yield no serious fumes or gases as would be the case for tunnels driven by conventional explosive methods. Boring machines are now essentially off-the-shelf equipment for rocks ranging from rather weak shales to strong hard sandstones and have been used with encouraging results in even stronger metamorphic rocks. With hydraulic or other automated handling of the ground-up waste rock, including ejection of the waste to the sea floor, tunnel boring in a rock strong enough to be fully self-supporting with a 15- to 20-foot-diameter bore can proceed at rates up to 5 miles per year for a cost of 1 to 1.5 million dollars per mile. Figure 16 shows a contemporary unlined, bored tunnel in a sandstone while Fig. 17 shows a bored tunnel requiring supports. In the latter instance, supports followed to within 4 feet of the tunnel face while boring was in progress. With modern day shaft and tunnel boring techniques, access to the sea floor from land can be carried out at depths beneath the sea of several thousand feet (to at least 10,000 to 12,000 feet) and to distances offshore of tens to hundreds of miles.

FIG. 16. Unlined Tunnel Driven in One Pass Through Sandstone. The tunnel is 19 to 21 feet in diameter depending on local rock conditions (Farmington).

FIG. 17. Tunnel Bored to a 21-foot Diameter in One Pass in Sandstone and Shale, Requiring Artificial Supports (Farmington).

FROM THE SEA

Direct access into the sea-floor bedrock by means of a lock system for passing through the sea-floor—water interface is a practice now within the technologic capability of this nation's industry. The final desired step-in sea-floor entry is to prove and to establish the feasibility of a method of direct access to the sea floor at a point remote from land. With such a method, manned undersea installations are possible at virtually any location even those remote from shore. If the cost of this direct access were not too great, then the method of direct access could quickly compete with the methods of tunnelling from shore, even adjacent to our own coastline.

The Rock-Site method of direct sea-floor access is shown schematically in Fig. 18, and consists of four steps that can be summarized as follows:

1. Drill a 5- to 8-foot-diameter drill hole a distance of 50 feet into competent sea-floor bedrock.[1]

2. Cement a lock tube into the borehole and then deballast the tube.

3. From inside of the tube, drill and grout as needed to consolidate the adjacent host rock with emphasis on consolidating the underlying rock.

4. Open the tube bottom and drill vertically downward into the bedrock until a suitable rock cover exists for the establishment of horizontal working and living spaces.

Although this method of entering the sea floor is new, there has been no new technology proposed in any of the four steps. The drilling of large diameter holes for mine shafts and ventilation winzes has been practiced for years in rocks ranging from incompetent to very strong and hard (Ref. 79). By using only a short length of hole, no bit or cutter changes will be needed during the drilling program and no rods need be added in the event the drilling is to be done submerged. The latter is certainly feasible with lowered packages and appears feasible from existing submersible hulls as well. Present-day drilling platforms and barges can work at depths comparable to the depths attainable by older fleet boats (World War II-type submarines.)

Since the desired hole into the sea floor is short, the drilling rate need not be high in order to result in a short drilling time, thus permitting considerable trade off between total drilling times, bit weights, and horsepower applied. Drilling from barges and platforms in an established petroleum-drilling and coal-boring technique that is available for immediate operations in water up to a few hundred feet in depth (Ref. 80 and 81). Drilling from large complex barges has been successfully demonstrated in 11,700 feet of water and is approaching operational reality in very deep waters such as the 14,000-foot depths contemplated by the MOHO project (Ref. 82–84). Drilling from packages lowered from a ship or hung on the exterior of a submersible has not been demonstrated to date, but studies are now in progress in this area industrially[2] and no serious drilling-system-design-problems are anticipated because there need be no bit changes or rod additions during the boring operations. Most questions regarding the feasibility of drilling from a submersible involve the problems of achieving enough load on the bit and preventing

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[1] From a technologic standpoint holes in excess of 25-foot diameter have now been drilled on land.

[2] Personal communication with Electric Boat Division of General Dynamics.

the submersible from rotating. Standard drilling methods of using heavy metal drill collars to achieve weight on the bit are certainly possible and thrusters or anchors on the submersible or barge can be used to prevent rotation. Some persons have even suggested letting the submersible rotate, using its drag as the source of bit torque. The author prefers the concept of drilling a pilot hole in which the pilot tools are expanded at a desired depth to act as an anchor, with the pilot tool drill rod then acting as a feed rod to pull the large diameter bit into the sea-floor bedrock. Whatever the method chosen for any particular undersea installation, the time required to drill 50 feet into the sea-floor bedrock should not be great. Advance rates of 1 foot per hour are reasonable, thus changes in weather and wave patterns will be a minimal hazard to the drilling system and offshore operations can be conducted in areas of only sporadic clement weather or open water, even when relying on existing drilling barges or platforms as the type of drilling system employed.

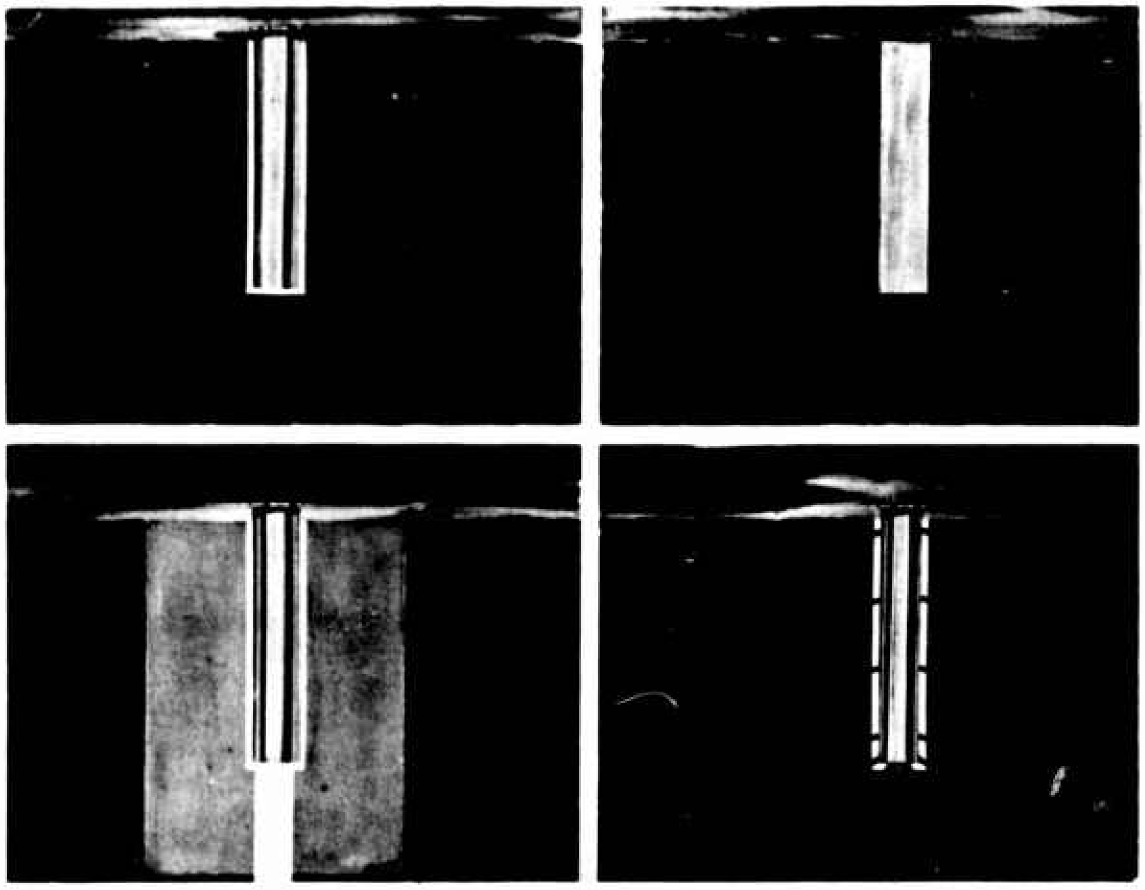

FIG. 18. Rock-Site Method of Direct Sea-Floor Access. Consists of four steps: (1) bore a hole into the sea floor, (2) cement a lock tube into the bore hole, (3) ring drill the surrounding host rock and pump cement or other grout into the drill holes to consolidate the host rock, and (4) drill on into the sea floor below the lock tube.

Rock-Site entry into the sea floor will require that the lock tube be set in some sort of rock that is at least competent enough to permit consolidation by grouting or other cementing operations. The length of lock tube and the depth of bottom mud over the sea-floor bedrock that can be economically dealt with will depend obviously upon the wind-wave-time hazards of the site and on the importance of the anticipated undersea installation (that is, is the cost of a long penetration in mud prior to bedrock justifiable).

Any location on the sea floor that consists of consolidated sediments strong enough to stand as an open bore can be entered to yield one-atmosphere working sites. A surprising amount of the deep ocean appears to be accessible competent bedrock. Some oceanographers now estimate that as much as 20% of the deep ocean may be bare rock while within a few tens of feet of the sea floor some 40% of the sea-floor area is expected to be competent rock. Even on the flatter continental shelves, there is considerable exposed bare rock that will permit Rock-Site-type lock-tube installations. For example, the continental shelf off the coast of Southern California appears to have some 10 to 15% of its area comprised of bare hard bedrock, with considerably more area being underlain by hard drillable sediments very close to the sea-floor surface.[3]

The second step of the sea-floor entry method proposed is to cement a prefabricated lock tube into the borehole. This procedure is no different than the setting of casing in any well. Once the lock tube is in place, cement is pumped into the annulus between the tube and the host rock, and allowed to set. Following this, the lock tube is dewatered or deballasted and can then be entered for its full length. Getting the lock tube into the drill hole can be done in many ways, ranging from lowering the tube from a barge or platform, to swinging the tube into the hole after the bit is swung out (when boring from a submersible), or by having the tube follow the bit into the hole. For most shallow continental shelf operations of today, lowering after drilling appears to be simplest, while for submersible-vehicle-based drilling, having the lock tube follow the bit into the hole appears to be simplest.

With the lock tube in the drill hole and cemented in place, continued access to the lock tube is the next consideration. To be of any value at all, a manned undersea installation must be accessible, and since the Rock-Site concept is for present-day operations with present-day technology, only simple or presently existing access concepts can be employed. Access to fully isolated continental shelf installations can be by means of submersible vehicles, by tubes to the surface, or by a combination of tubes and vehicles. The most economical method of access will depend on the degree of surface-water roughness, the depth of the installation, and

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[3] Personal communication with Roland von Huene and David W. Scholl of this Station.

the degree of secrecy required. Submersible vehicles suitable for access use with no modification are in the very near future, drawing upon the plans and experiences to be gained in the next few years from the Navy Deep Submergence Systems Project in general, and from the URV programs in particular, and upon the now emerging fleet of industrial vehicles (Ref. 85-87). Submersible vehicles with a short range that can couple onto a lock tube present no technologic difficulties, but they do not exist as widely available off-the-shelf equipment at the present time.

Two methods of access are especially attractive where fully submerged operations are not required. One is to use a telescoping system that is either an integral part of the lock tube or that can be mated to the top of the lock tube, and the second is to use a tube that can be pivoted about the lock seal, that is, raised for access or swung downward and sunk to one side for protection from rough weather. Figure 19 shows line sketches of these two systems plus a sketch of a floating instrument platform (FLIP-type) system which could also be employed with existing technology (Ref. 88 and 89). Older obsolete fleet boats or nuclear submarines could also be fitted with a lock system that could mate with Rock-Site lock tubes, thus enabling under ice and moderately deep undersea operations that would be free of immediate surface-support requirements.

The question of the practicality of large water-tight bulkheads and doors is often raised at this point, since the lock tube will obviously need to be opened and closed many times. Figure 20 shows a person standing in a bulkhead and pressure lock unit that is in present industrial use. This unit operates against 1,200 feet of head and has been successfully cycled many times. With larger locks, such as those intended for submarine vehicle entry, the problems of distortion and pressure bleed-off rates in the lock walls become more important than with small metal-lined locks. Tunnel openings that undergo cyclic stressing will tend to crack and their walls will tend to spall, especially if the pressure is dropped rapidly. Figure 21 shows a tunnel section that has been cycled a number of times to 520 psi and that failed after the pressure was released during one of the cycles. The author believes this specific failure to be the result of tunnel wall flexure followed by cracking, a result of the rectangular tunnel outline.

The third step in the lock-tube emplacement program is to grout the host rock surrounding the tube, thereby consolidating the host rock and providing both strength and a barrier to large water inflows. Grouting from inside of drill holes, shafts, and tunnels has been practiced for years (Ref. 90 and 91).

The final access step to the sea floor is to bore downward to some convenient depth within the sea floor below. This operation requires the insertion or assembly of a drill within the lock tube, unless the lock tube had followed the drill into the bore hole with the drill allowed to remain in the hole; an initial source of power to operate the drill; and

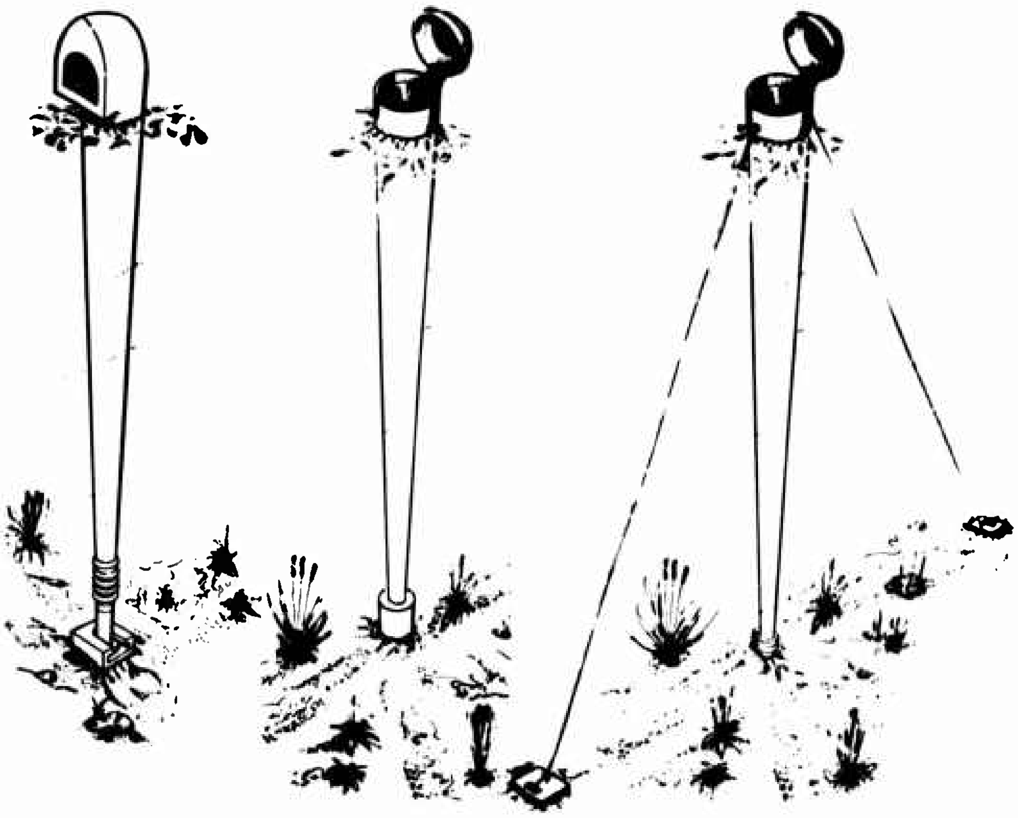

FIG. 19. Methods of Achieving Access to Relatively Shallow Continental Shelf Installations. (a) A FLIP-type vehicle, (b) telescoping tube, and (c) swinging tube.

FIG. 20. Pressure Lock and Bulkhead Successfully Used With 520 psi Water Pressures (Ruby Hill).

sufficient life-support capability to maintain the drilling crew. Power can come from a submersible support boat or vehicle, from a support barge, or from a temporary bottom-sitting power plant. Life support can also come from a submersible support boat or from a tube raised to the surface. In the case of sea-floor entry based upon present-day platform and barge techniques, there are some obvious advantages to drilling much more than merely 50 feet into the sea floor prior to the setting of the lock tube, which can in itself be longer and provide more working room prior to manned entry into the hole already drilled below the lock tube. Cuttings disposal for this phase of the drilling operations can be by pumping overboard as a slurry or by dewatering and storage on board a submersible for dumping elsewhere.

FIG. 21. Section of Tunnel Wall. Driven in grouted dolomite breccia that has failed after a number of pressure cycles to 520 psi (Ruby Hill).

This section of the report has consisted of a consideration of the problems of sea-floor access. Methods of access have been outlined that are feasible and that rely entirely on existing methods and equipment. Cost estimating for sea-floor access based upon shaft and tunnels from land is fairly precise, and the costs are no different than those encountered in everyday mining practice within the raw material industry. The cost of sea-floor access directly from within or on top of the sea above is more difficult to estimate since the method has not actually been tried as a single integrated operation although each of the requisite steps has been conducted at one time or another by industry. The cost of access directly into the sea floor, including the lock tube and a raisable access tube is not believed to be greater than twice the cost of the comparable shaft on land, that is, a direct sea-floor access system will be in the 4 to 8 million dollar price range, exclusive of the cost of constructing the boring barge or platform which may be leased or which may be in hand prior to the inception of any single Rock-Site-type project.

With this price tag, installations over 1 to 2 miles from shore can be more cheaply installed from Rock-Site entry locks on a cost-of-hole basis. An over-all system cost analysis that includes costs for men and materials, the cost of life support, and a risk factor for direct access (which is untried for some given area of sea-floor rock mass) will require that installations be several miles from shore before direct access from the sea floor becomes competitive with shore-based tunnel and shaft-access systems.

Shaft sizes can range from a minimum for manned access of 24 inches in diameter to about 16 feet in diameter. A shaft size initially of 5 to 8 feet in diameter has been selected as permitting the installations of quite large equipment including a disassembled 5-Mwe reactor, an assembled 500-kilowatt-electrical-(kwe) reactor (which may be in several discrete packages), and a disassembled tunnel boring machine. The potential trade-offs between bit size, bit weight, available power, and available time have already been mentioned, and these considerations can then be mixed with the consideration of minimum possible imported part size to yield a shaft-size decision for a specific site.

WORKING SPACE

Merely putting a man into the sea floor inside of a lock tube has relatively little to recommend it except perhaps as a means of repairing and installing equipment that otherwise operates unattended. Manned sea-floor installation requires room for the performance of useful tasks, for supply storage, for crew and family accommodations, for recreation facilities, for power, for life-support equipment, and for pumping installations.

Power in existing undersea mines today is usually compressed air, electricity, or diesel engines. Electricity and compressed air are certainly the best for fully submerged undersea operations as they do not in themselves contribute to the life support or ventilation burden when used in confined spaces.

During the establishment of an initial horizontal working space, as during the initial access boring operations, power and life-support gases must be provided from the outside. Power can be from shipboard, from a temporary platform, from an anchored barge, or from a bottom-sitting power package adjacent to the lock tube. Life-support gases will continue to be obtained from the supply and power boat if a submersible is used, or from a snorkel-type tube to the surface if the surface is free of obstructions and not too distant, or can be produced by means of electrolysis. As a matter of fact, the use of snorkel tubes to the surface allows the use of cheap, off-the-shelf internal combustion generating equipment in bottom-sitting power packages or within the sea-floor installation itself. As a general rough estimate, power needs during access shaft boring and the initial working space establishment will be 500 kwe. A large pumping load will require an upward adjustment of this figure, suggesting for such installations the use of two or more reactors as a source of power.

Given power, air, and crew access, the bottom of the lock tube is opened and boring continued on downward into the sea floor. Waste rock or cuttings are slurried and pumped overboard. Boring, being noncyclic and free of atmospheric pollution can continue on a round-the-clock basis even though the lock tube may be a little cramped and crowded initially. The author has worked inside of a drill hole 36 inches in diameter (but admittedly prefers a larger drill hole when possible) and has done extensive work inside of a 44-inch-diameter opening.

Once an adequate depth of rock cover exists overhead, between the elevation of the desired horizontal openings and the sea floor, conventional drilling and light blasting or else chipping and boring combined can open out a lateral room with sufficient horizontal floor space to permit the installation of pumps, life-support gas generation equipment (if desired), and the initial in situ power plant of one or more 500-kwe-size nuclear reactor plants. This equipment will now free the installation from surface or shipboard support save for spare parts, supplies, and crew changes. The actual size of the initial power package needed within the sea floor will depend on the type of life-support system used, the intended rate of advance both vertically downward and laterally at the main working level, and on the anticipated leakage rate or pumping load. Nuclear power packages in increments of 500 kwe are of a size that will fit within the 5- to 8-foot lock-tube diameters anticipated. Furthermore, air-breathing installations can be used for life support in shallower installations through the use of snorkeling systems that consist of tubes to the surface, presuming the air-water interface to be accessible.

When the vertical access shaft reaches some desired depth, say 500 to 1,000 feet below the sea floor, the next step in establishing a useful Rock-Site installation is to construct a permanent working and living complex. This complex will have crew and family quarters, recreation facilities, community facilities, the main power plant, and life systems plus access tunnels to laboratory spaces, supply dumps, and to weapon and sonar sites, major-sized vehicle locks or to other installations, depending on the intended uses of the Rock-Site installation.

The main operating level should be constructed by boring since this procedure yields a strong, smooth tunnel and places no burden on the ventilation system. Using boring methods, the main operating complex can be a series of parallel rooms, a long strung out linear array, or perhaps best, a spiral that is then cut by a series of "radial" access tunnels. Accurate spiral boring is within the guidance capability of present-day boring machines.

Excavation costs for the main portion of the installation will be no different than for ordinary mining operations in a comparable rock type. Life support and power costs will vary greatly, depending on the type of source employed. Air-breathing installations drawing air from the water surface will be cheap compared to the use of reactors and self-contained, life-support systems, of the type used today on submarines, but the latter can be used in deep water or in areas where the water-air interface is inaccessible.

Reactor costs, for the main operating power in large installations, vary strongly depending on whether you buy the first model or a later edition, and on whether or not the seller thinks a continuing market will exist. Thus a 5-Mwe installation, small enough to transport through an 8-foot lock tube (or a little less) will for the first model cost between 15 and 20 million dollars installed. These reactors will be cooled by circulating sea water using convective or force circulation systems or by the use of sump water resulting from installation leakage, prior to its ejection to the sea floor.

In this section of the presentation, the working space portion of establishing undersea bases has been presented. Once beneath-the-sea-floor access is achieved, through either a shaft and tunnel from land or through a lock tube in the sea floor, all operations within the sea-floor bedrock itself are identical to present-day routine industrial activities save for the life-support gas generation and the hydraulic ejection of waste rock to the sea floor, though these two are demonstrable proven processes. Costs for working space construction will vary with the rock conditions. Tunnel costs of $300 per foot will cover present-day boring operations, some of which are closer to $200 per foot in even fairly strong sandstones. Costs can run to as high as $1,000 per foor for tunnels driven in very weak porous rocks with high water pressures and very high flow rates, requiring extensive consolidation and cementation.

An estimate of the cost of the fully isolated installation shown in Fig. 22 is 25 to 50 million dollars. This installation includes a 5-Mwe power supply, and as shown has a submersible vehicle lock for transport and deep-sea explorational purposes, and a glass observation dome (Ref. 92 and 93).

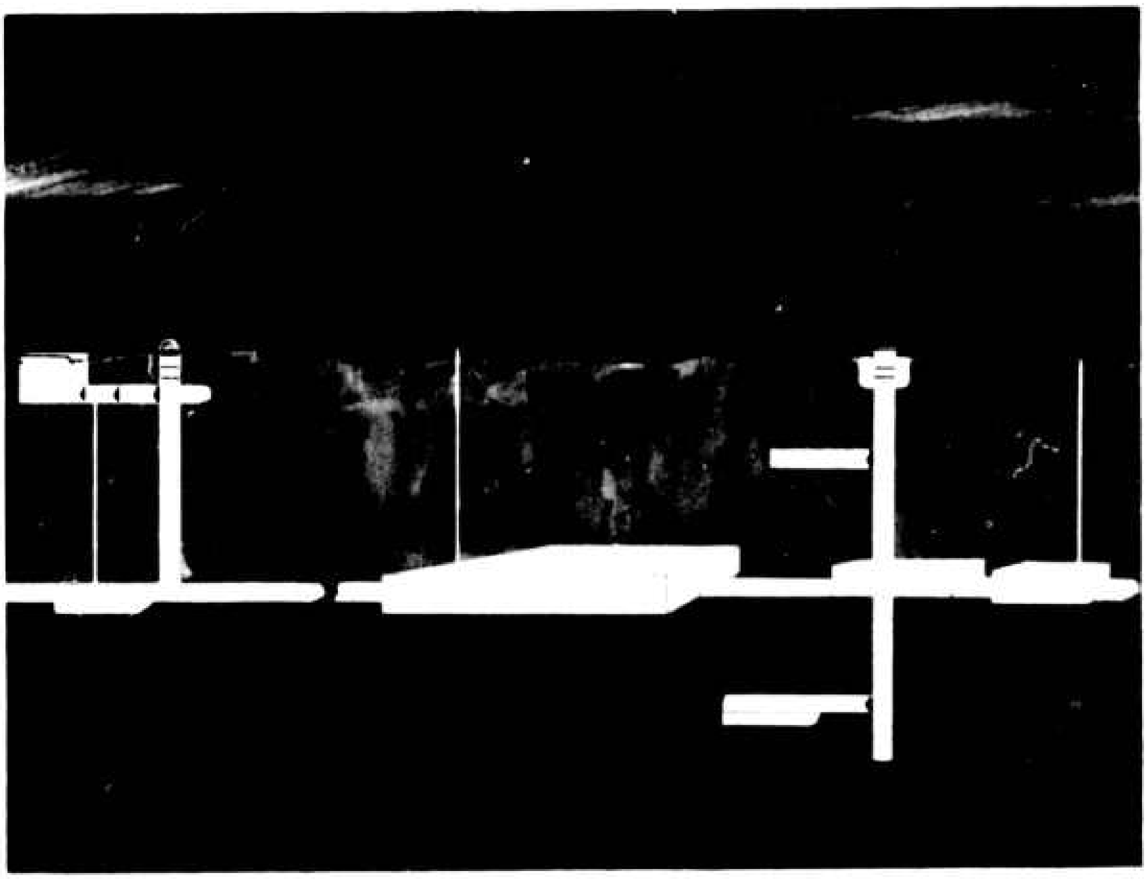

FIG. 22. Fully Isolated Rock-Site Installation. Comprised of an initial lock tube, and access shaft, and initial life support and power chamber, reactor chamber, drill holes to the sea floor for reactor coolant circulation, working and living space, a glass-domed observation tower, and a vehicle lock with associated sumps.

SEA-FLOOR ACCESS FROM WITHIN

As a matter of technical interest, going out into the sea water from inside the sea floor is much simpler than going into the sea floor from the water. The rationale for this statement is simple. Drilling of a large diameter hole for lock-tube emplacement from the sea-water side of the bottom is a problem involving limited power, working room, and bit load. When drilling from within, be the drilling horizontal to vertical in aspect, there will be no shortage of power since the main station power plant can be utilized and there will be no shortage of bit load since hydraulic jack or ram-type feed systems can be used. Leakage during and after the bit breakthrough to the water can be controlled by oil-well-type blowout preventers. In the case of very large vertical drill holes, as with horizontal locks, the entire boring machine can be run flooded to sea-water ambient conditions during the final breakthrough phases of the lock-boring operation.

Lock-tube emplacement in a hole drilled from inside can be from the outside or from the inside. In the latter case, there are several practical options. The lock tube can follow the drill as a part of the string of tools or it can be pushed into position after the drill has been retracted into a sump. All large, especially multiple pass drilled lock tubes, can with present technology be most easily bored from within the sea-floor rock mass. With large boring equipment, especially when operated flooded, there is no present technologic reason why locks of a size to accept large submersibles cannot be constructed close to the sea floor, and then have the covering rock mass removed by a combination of boring and gentle explosives techniques such as presplit and smooth wall blasting (Ref. 94 and 95).

WHY ROCK SITE - THE ADVANTAGES

As soon as someone proposes to do something differently, a flurry of argument breaks forth as to "why," and "what good is it," and "obviously, it is impossible or it would have been done already." These discussions are healthy for all concerned as they take some of the shine off of new ideas and they get other persons besides the original idea-formers involved in contributing thoughts, problems, and solutions in support of the original concept.

As a government project, compared for example with many missile and space programs, the Rock-Site concept of establishing permanent undersea installations does not appear to be highly expensive. Some of the advantages of the Rock-Site method of sea-floor occupation over other types of sea-floor access and utilization are worth a specific mention. When compared with barges and platforms per se, the Rock-Site method of in-the-sea-floor installation establishment offers the following:

1. Weather and waves are not a hazard.

2. All equipment is accessible to ordinary technicians and laborers.

3. The working volume or space can be expanded cheaply to meet future operational needs once the original installation is achieved.

4. The Rock-Site installations can be placed at great depth beneath the sea floor; their openings can be numerous and scattered; and access to the installation is absolutely controlled by the base occupants. If desired, reactor waste heat can be internally stored or dissipated into the earth by means of fluid injection into deep, permeable zones in order to prevent an undesirable heating of the surrounding water. With near the sea-floor installations, some heat will be needed to maintain a comfortable installation, since rocks near the sea floor will probably be at or near the deep ocean temperature of only a degree of two centigrade.

5. Surface hazards such as accidental ship-caused damage and floating hazards are avoided.

With respect to bottom-squatting structures, Rock-Site installations show the following advantages:

1. Water mass "weather" is not a problem for Rock-Site installations, but people working on the sea floor will have to contend with currents, shear on structures, and numerous other water "weather" problems.

2. The working volume is "thin-skinned," and can be quite large, avoiding the tendency for "thin-skinned" structures to suffer catastrophic flooding and high leakage rates given even minor structural damage. A leak developing through several hundred feet of rock can be grouted from within by means of drill holes, a leak developing through an inch or two of steel is apt to be hard to control, especially from inside.

3. Damage from accidental ship activities is far less.

4. All facilities and equipment (save the outside of the lock-tube door, are accessible at all times to ordinary technicians and laborers).

5. Damage from drift ice and ice-flow groundings is avoided.

6. Structures within the sea floor can easily be made large and comfortable enough to permit the quartering of crews and their families for extended periods of time, and can be made large enough to serve as supply and repair depots for large submersibles.

SITE SELECTION CONSIDERATIONS

The selection of a suitable location for a Rock-Site installation will be based on the following general considerations:

1. Politico-economic - The installation must be at a geographic location of some value to the nation or company that constructs it.

2. Geologic - The type of bottom, depth of mud, and anticipated rock types below the sea floor must be of a type that will allow Rock-Site activities.

3. Topographic - The shape of the sea floor must permit the type of locks or other desired installations.

Politico-economic considerations will outline the general geographic regions in which Rock-Site undersea installations might be of benefit. As an example, rather than establish major nuclear power supplies on land in highly unstable emerging nations, such stations could be put offshore where they would be free from damage during periods of political upheaval.

Geologic considerations require that the bottom have a competent bedrock mass within an attainable distance of the sea floor. If the installation is to be extensive, a large mass of rock that is free of serious leakage problems will be needed. Almost any type of rock can be used for Rock-Site installations but a rock strong enough to be self-supporting and low enough in combined permeability and porosity to preclude large water flows is desired. A favorable rock mass can be at any attitude, but a horizontally oriented installation appears cheapest and easiest to build.

Rock masses free of fractures and faults need not be present. Many undersea fault zones have been found to be free of leakage due to the sealing action of the crushed rock (gouge) filling the fracture zone. Indeed, some undersea coal mines for years have practiced long wall mining during which the sea floor is allowed to collapse, relying on intervening shale horizons to provide a continuing seal against the waters above. Rock masses with overlying or interlayered shales and muds are least apt to leak. Rocks of all types can be protected from leakage by coverings of bottom mud or ooze. Complex fault systems with their attendant gouge zones can protect large blocks of otherwise highly permeable rock from leakage although water statically stored in such a rock mass can be a temporary problem. Volcanics, especially blocky and high vesicular lavas can be protected from leakage by interflow beds of tuffaceous material or by alteration along joints and flow planes. Any type of rock strong enough to stand unsupported can be used for a Rock-Site installation as can many rocks requiring grouting consolidation and even extensive timbering or other artificial support.

Topographic considerations dictate the type of entry locks and the depth to which installations must be placed beneath the point of initial sea-floor entry. A horizontal submersible entry lock will require a steep, preferably vertical, canyon wall or slope. An observation tower may require a broad flat plain or a prominent hill such as a seamount. The terrain should match the needs of the installation as much as possible.

SOME INDUSTRIAL IMPLICATIONS

The industrial implications of a successful Rock-Site installation will be far reaching and of great national importance. Rock-Site installations can provide permanent petroleum drilling sites not only on the deep continental shelf but in areas beneath both intermittent and permanent ice cover. These same type of drilling sites can serve for the production of geothermal steam and brine, enabling in the near future the exploitation of deposits such as those now suspected in the floor of the Red Sea (Ref. 96).

For hard minerals production, Rock-Site-in-the-sea-floor installations will enable undersea mining to be conducted beneath a considerable depth of water and great distances offshore. By the use of observation towers plus scrapers and dewatering locks, Rock-Site mining installations will enable the mining of sea-floor nodules and offshore placer deposits without the constant hazards of wind and wave damage that are inherent in surface-ship-type operations.

Rock-Site-concept utilization converts any coastline to a deep water port facility capable of handling petroleum products and mineral slurries to and from surface ships by means of hoses with present technology and if submersible cargo vessels eventually result, other less easily transportable cargoes can be handled as well.

Rock-Site installations will make ideal offshore nuclear-power-plant sites using convective sea-water cooling, and can provide the working space and power needed for undersea booster pumping plants for pipeline systems paralleling a coastline.

CONCLUSIONS

Using only the tools and techniques to todav's raw materials industry, manned installations of a large size containing a one-atmosphere shirt-sleeve environment can be built today on much of the world's continental shelf region. With a modest extension in undersea vehicle capabilities, large manned installations can be established at almost any location on the continental slopes, the deep-ocean floor, and on seamounts and ridges.

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13 ABSTRACT

Large undersea installations with a shirt-sleeve environment have existed under the continental shelves for many decades. The technology now exists, using off-the-shelf petroleum, mining, submarine, and nuclear equipment, to establish permanent manned installations within the sea floor that do not have any air umbilical or other connection with the land or water surface, yet maintain a normal one-atmosphere environment within. This presentation briefly reviews the past and present in-the-sea-floor mineral industry. The methods presently practical for direct access to and from permanent in-the-sea-floor installations are outlined, and the specific operations and types of tools indicated. Initial power requirements and cost estimates are included.

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